PHASE - An event generator for six fermion physics at the LHC

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PHASE is a Monte Carlo event generator, under construction, for all Standard Model processes with six fermions in the final state at the LHC. It employs the full set of tree level Feynman diagrams, taking into account fermion masses for b quarks. The program can generate unweighted events for any subset of all six fermion final states in a single run, by making use of dedicated pre-samples. An interface to hadronization is provided.

1. Introduction

At future colliders, many-particle final states will be accessible with much more statistics. Among these, six fermion signals are of particular interest for their relevance in top-quark physics, Higgs boson production in the intermediate mass range, vector boson scattering, and quartic gauge boson coupling analyses.

Typically, multi-particle final states can come from the decay of intermediate unstable particles that are produced as resonances in subprocesses. Relying on this, the most commonly used generators Pythia [1] and Herwig [2] are entirely based on the *production* $\times$ *decay* approach, i.e. narrow width (NWA) and effective vector boson approximation (EVBA). While the general expectation is that NWA (with possible improvements by spin correlation between production and decay or by Breit-Wigner convolution) can give an order ten percent unaccuracy, the EVBA is surely more problematic. In the basic leading-log formulation, it does not allow to freely implement any kind of kinematical cuts. The parton coming out after the vector boson emission is in fact produced in a fully inclusive way. Even in its improved realization, which accounts for the exact phase space, the EVBA cannot always reproduce the correct kinematics and event rate. The result strongly depends on the applied cuts, and there is no unique recipe. Therefore, its reliability must be always cross-checked against a complete program implementing exact calculations.

A further reason for going towards full computations is connected to gauge invariance and the appearance of strong and extremely delicate cancellations at high energy among Feynman diagrams contributing to the same final state. These interferences can take place both within the signal diagram set and between signal and irreducible background diagrams. Thus exact matrix elements must be computed. This means evaluating thousands of diagrams for a huge variety of possible processes.

In the last decade, a big effort has been dedicated to the implementation of event generators for multi-parton production. At present, the following codes are available: `Amegic` [3], `CompHEP` [4], `Grace` [5], `Madgraph` [6], `Phegas & Helac` [7], `O'Mega` & `Whizard` [8]. These are *multi-purpose* generators, which in principle can compute any tree level process. A different approach is given by event generators *dedicated* to specific classes and topologies of final states. A recent example of this kind of generator for LHC physics is `Alpgen` [9].

2. PHASE: PHact Adaptive Six-fermion Event generator

In this section, we present the general features of the Monte Carlo event generator PHASE [10], which is fully *dedicated* to six-fermion physics. In its first version, the PHASE project is designed for all Standard Model processes $pp \to 6f$ in lowest order.

2.1. Processes

At the present stage, PHASE includes $O(\alpha^6)$ electroweak processes with a neutrino in the final state, $pp \to 4ql\nu_l$. By making use of symmetries, all these channels can be classified into 16 groups which are enumerated in Table 1. By selecting two initial quarks in each particle group, one can obtain all possible processes whose number is given in the last entry. Taking into account charge conjugation and family symmetry, one ends up with more than one thousand processes. In some of them, fermions can only be paired into charged currents (4W), in others into two charged and two neutral currents (2Z2W) or into a mixed combination (2Z2W+4W).

It should be noticed that the amplitudes of the above mentioned 16 groups are not all independent. They are in fact combinations of only 4 basic sets of Feynman diagrams (101, 211, 22, 94). This means that all thousand processes can be implemented using just few building blocks. The immediate advantage is that any modification, like including new couplings or vertices, has to be done only in a very restricted area of the program and then it will be automatically communicated to all processes.

2.2. Helicity amplitudes

PHASE works with exact matrix elements, thus providing a complete description of signal and irreducible background. All amplitudes are written with the help of the program PHACT [11], which is based on the helicity formalism of ref. [12]. This method allows one to calculate parts of diagrams of increasing size and complexity, and store them for later use. In this way, common subdiagrams are evaluated just once, with a substantial efficiency gain. The formalism is appropriate both for massless and massive fermions. In PHASE, fermion masses are exactly taken into account for b quarks.

2.3. Phase space integration

Since a single process can contain hundreds of diagrams, the amplitude peaking structure is generally rather complex. As a consequence the 15-dimensional phase space has untrivial kinematical regions corresponding to the matrix element singularities. In order to gain in accuracy and efficiency, PHASE relies on a new integration method, which combines together the adaptivity principle á la VEGAS [13], and the multi-channel strategy. The outcome is that PHASE adapts to different kinematical cuts and resulting peaks with good efficiency. In contrast to the pure multi-channel approach, where one has to introduce a phase space parametrization with appropriate mappings, called channel, for each propagator appearing in the amplitude, here a maximum of four channels is required. Moreover, owing again to adaptivity, only a rough estimate of the relative weights of the channels is sufficient for an accurate integration. The drawback is that each channel must be integrated separately.

During the integration of the single process, integration grids will be generated (one for each channel). These grids optimize the integration itself and constitute the basic ingredient for the so called *one-shot* event generation we are going to describe in the next section. The important feature of the integration grids is that they are computed just once, with the loosest set of cuts in order to retain as much information as possible, and stored for later use.

2.4. *One-shot* event generation

After generating the integration grids, the *one-shot* procedure can start. This is one of the main features of PHASE. In fact, it allows the user to generate unweighted events not on a process by process basis but for any possible set of processes in just a single run, giving at the end a complete event sample where all included final states appear in the right relative proportion.

The general method for the *one-shot* generation is very similar to the one used in WPHACT and described in ref.[14], but generalized to six-fermion

Table 1
Processes and groups

particles	type	diagrams	process number
$c\bar{s}d\bar{u}c\bar{s}l\bar{\nu}$	4W	202=**101**×2	6+2
$u\bar{u}u\bar{u}c\bar{s}l\bar{\nu}$	2Z2W	422=**211**×2	6+2
$u\bar{u}c\bar{c}c\bar{s}l\bar{\nu}$	2Z2W	422=**211**×2	10+1
$u\bar{u}s\bar{s}c\bar{s}l\bar{\nu}$	2Z2W	422=**211**×2	10+1
$u\bar{u}b\bar{b}c\bar{s}l\bar{\nu}$	2Z2W	233=**211**+22	15+0
$d\bar{d}d\bar{d}c\bar{s}l\bar{\nu}$	2Z2W	422=**211**×2	6+2
$d\bar{d}c\bar{c}c\bar{s}l\bar{\nu}$	2Z2W	422=**211**×2	10+1
$d\bar{d}s\bar{s}c\bar{s}l\bar{\nu}$	2Z2W	422=**211**×2	10+1
$d\bar{d}b\bar{b}c\bar{s}l\bar{\nu}$	2Z2W	233=**211**+22	15+0
$c\bar{c}c\bar{c}c\bar{s}l\bar{\nu}$	2Z2W	1266=**211**×6	3+2
$c\bar{c}b\bar{b}c\bar{s}l\bar{\nu}$	2Z2W	466=(**211**+**22**)×2	10+1
$s\bar{s}s\bar{s}c\bar{s}l\bar{\nu}$	2Z2W	1266=**211**×6	3+2
$s\bar{s}b\bar{b}c\bar{s}l\bar{\nu}$	2Z2W	466=(**211**+**22**)×2	10+1
$b\bar{b}b\bar{b}c\bar{s}l\bar{\nu}$	2Z2W	610=(**211**+**94**)×2	6+2
$u\bar{u}d\bar{d}c\bar{s}l\bar{\nu}$	2Z2W+4W	312=**101**+**211**	15+0
$c\bar{c}s\bar{s}c\bar{s}l\bar{\nu}$	2Z2W+4W	1046=**101**×2+**211**×4	6+2

processes. Given the integration grids described in the previous section, `PHASE` will read from these files all necessary information and build up for every single channel its probability and a maximum normalized to it. According to this probability, one channel will be extracted at a time, and an event will be generated with a frequency determined by its grid. The event will be then compared with the normalized maximum in order to keep or reject it. The procedure is repeated until the required number of unweighted events is produced.

The generated events can then be passed to Pythia, in order to simulate observable final states via showering and hadronization. In this way, one can have a complete and accurate tool for realistic experimental simulations. This step is performed according to the "Les Houches accord" [15], a set of common blocks for passing event configurations from parton level generators to parton shower and hadronization packages.

3. Results for Vector boson scattering

We consider a typical channel including the subprocess $WW \to WW$ at the LHC. We analyze the process $ud \to udc\bar{s}\mu\bar{\nu}$ in the region where we have the distinctive two forward jets signature. To this aim, we apply the following cuts:

$$E_T(u,d) \geq 20 \text{ GeV} \qquad P_T(u,d) \geq 10 \text{ GeV}$$
$$-5.5 \leq \eta(u) \leq -1 \qquad 1 \leq \eta(d) \leq 5.5$$
$$-10 \text{ GeV} \leq M(c\bar{s}, l\bar{\nu}) - M_W \leq 10 \text{ GeV}$$

The first effect we investigate is connected to gauge invariance. It was already pointed out by Kleiss and Stirling in an old paper [16] that selecting only the subset of vector boson signal diagrams from the full amplitude could give meaningless results. This argument relies on the fact that the delicate gauge cancellations get destroyed by the off-shellness of the two initial vector bosons. We have checked this issue in more detail. In Table 2, we present the total cross section and the pure vector boson scattering signal for different Higgs masses, in unitary gauge. As one can see, the full cross section is two order of

Table 2
Gauge invariance and cancellations.

M_h	signal (pb)	total cross section (pb)
120 GeV	0.2106672	0.1319138E-02
200 GeV	0.2174115	0.7960299E-02
500 GeV	0.2114054	0.2804993E-02
2000 GeV	0.2100076	0.1490797E-02
No Higgs	0.2099891	0.1468983E-02

magnitude smaller than the signal. This poses an important question on what kind of signal definition one can give at high energy. This issue should receive more attention. In Fig.1 we show the WW invariant mass distribution for different helicity configurations of the two reconstructed W's. Starting from the left, from top to bottom we plot the UU, TT, TL and LL contributions, where U, T and L are for unpolarized, transverse and longitudinal gauge boson. Additional $P_T(c\bar{s}, l\bar{\nu}) \geq M_W$, $E_T(c, \bar{s}, l) \geq$20 GeV and $P_T(c, \bar{s}, l) \geq$ 10 GeV cuts are included.

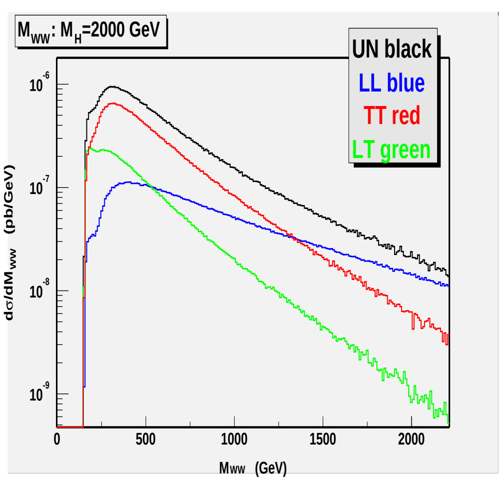

Figure 1. WW invariant mass distribution.

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